

PROSPECTS FOR VLBI DETECTION OF PLANETS

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ABSTRACT The precision of astrometric VLBI measurements of radio-emitting stars has improved significantly during the past several years. For some stars whose radio flux density is only a few mJy the formal error and epoch-to-epoch scatter in position is ≈ 200 –600 microarcsec. The intrinsic signal/noise ratio in the data should allow a further order of magnitude improvement in astrometric precision as sources of systematic error are better understood and corrected. Wider bandwidth VLBI data recording systems currently under development will allow precisions of ~ 3 microarcsec if the measurements are limited by thermal noise. At this level planets with mass $\geq 0.1 \times M_{\text{JUPITER}}$ could be detected for the nearest radio emitting stars.

INTRODUCTION

Astrometric monitoring of the minute displacement of a star around the barycenter of the system that includes possible planetary companions has been an indirect method for planet detection for several decades at optical wavelengths (van de Kamp and Lippincott 1951). The motion of a single planet in a circular orbit around a star causes the star to undergo a circular motion around the star-planet barycenter. When projected on the sky, the orbit of the star appears as an ellipse with angular semimajor axis θ given by:

$$\theta = \frac{m_p}{M_*} \frac{a}{d} \quad (1)$$

where θ is in arcseconds, the semimajor axis a is in AU, the mass of the planet (m_p) and the mass of the star (M_*) are in solar masses, and the distance d is in pc. For example, if the solar system were observed from a distance of 10 pc the presence of Jupiter would be revealed as a periodic elliptical displacement in the Sun's position, with an amplitude θ of 0.5 milliarcsecond (mas) and a period of 11.9 years.

Optical astrometry has generally been limited to a precision of a few tens of mas but the best measurements are now at the 1 mas level (Gatewood *et al.* 1992). Technical advances in Very Long Baseline Interferometry (VLBI) with the Mark III data acquisition system (Rogers *et al.* 1983) have provided sufficient sensitivity to reliably detect radio emitting stars over the last few years. We have carried out VLBI measurements of the position of the radio star σ^2 CrB since 1987 and demonstrated that the level of precision is 0.2 mas during 5 years. This level of precision is not SNR-limited and might reach 20 μ as if all systematic errors could be removed by an improved strategy of observation or data analysis. Such a high level of astrometric precision makes the VLBI technique a powerful new tool for planetary searches.

RADIO-EMITTING STARS

There are about 400 stars that exhibit radio emission as compiled by Wendker (1987). About half of these stars exhibit thermal free-free emission from very large ionized circumstellar envelopes that are fully resolved by VLBI observations. The other stars exhibit non-thermal radio emission (gyrosynchrotron, synchrotron, coherent emission mechanisms) with typical source sizes of a few mas or less. These non-thermal radio emitting stars belong to a wide variety of physical classes, *e.g.* X-ray, RS CVn, Algol, dMe, FK Com, δ Tauri. Many of these stars can be detected by the sensitive Very Large Array (VLA) in New Mexico, but are too weak to be detected by VLBI. Their radio flux density is only a few milliJansky (mJy) or less, *i.e.*, 100-1000 times weaker than compact extragalactic radio sources usually observed by VLBI. Nevertheless, 30 stars can be detected by phase-referenced VLBI observations and this number will grow with future improvements of the technique.

We have selected 11 radio emitting stars with non-thermal emission (7 RS CVn, 2 X-ray and 2 Pre-Main-Sequence stars) for a high-accuracy VLBI astrometric monitoring program in support of the Hipparcos mission. The initial motivation of this program was to measure the radio positions and proper motions of radio stars which are optically bright enough to be observed by the Hipparcos satellite. This will allow us link the future Hipparcos optical reference frame to an extragalactic [III.s.ii] celestial reference system (Lestrade *et al.* 1992).

The Hipparcos mission is expected to end in late 1993 or early 1994, and our supporting VLBI observations of radio emitting stars will end in mid-1994. We intend to continue our VLBI observations of stars beyond this date with increased accuracy to search for extra-solar planets around the 7 stars in Table III below. This table includes 5 of the closest stars from our Hipparcos program.

PHASE REFERENCED VLBI TECHNIQUE FOR HIGH-PRECISION ASTROMETRY OF WEAK RADIO SOURCES

VLBI is an astronomical technique using an array of antennas (two or more) separated by baselines of a few thousand kilometers which simultaneously observe the same radio source and record its continuum signal over a limited bandwidth, typically a few tens of MHz, on magnetic tapes. After the observations, the tapes are reshipped to a processing facility and the recorded signals from each pair of antennas are cross-correlated on a specialized digital processor. The observations are usually carried out at centimeter wavelengths (1 to 30 GHz). Coherence of the radio signals recorded at antennas separated by long distance is possible by locking the heterodyne reference frequency of the receiver at each site to a frequency standard such as a Hydrogen maser that has a stability of $\sim 10^{-14}$ s/s. This allows coherent cross-correlation over 5-15 minutes at centimeter wavelengths. Consequently, the observed radio source must have a flux density high enough to be detected over a similar integration time. This is the reason why VLBI is less sensitive than the VLA, which is a connected interferometer with which one can integrate data for several hours if high sensitivity is required. Of course, VLBI has a much finer angular resolution than the VLA reaching < 1 mas on intercontinental baselines. At the VLBI processor, the cross-correlation of the recorded signals leads to the measurement of the amplitude and phase of the complex visibility induced by the source brightness distribution convolved with the beam of the antenna pair for the duration of each scan (typically a few minutes).

As mentioned above, the coherence time in standard VLBI is severely limited to less than ~ 15 minutes by the independent frequency standards at the VLBI stations. When a radio source is so weak that it cannot be detected within this duration, one has to resort to the phase-referencing VLBI technique. This allows multiple scans to be combined in a single coherent integration period, as we have demonstrated by our Hipparcos-related VLBI astrometric program. A reference for the VLBI phase must be established by observing an angularly nearby strong extragalactic source alternately with the weak program source with a cycle time of a few minutes (less than the coherence time). Such a phase-referencing technique in VLBI allows increased sensitivity through use of much longer integration times (several hours) with minimum coherence loss. This strategy also allows high-accuracy differential astrometry because the prime observable used is the VLBI phase. The VLBI interferometer produces milliarcsecond fringe spacings on the sky, and the phase of the complex visibility derived from cross-correlation can be used to measure the position of the radio source with an uncertainty corresponding to a small fraction of this fringe spacing. The phase-referencing VLBI technique as applied in our VLBI astrometric program is described in detail in Lestrade *et al.* (1990).

VLBI OBSERVATIONS OF THE RADIO STAR σ^2 CrB

σ^2 CrB is an RS CVn close binary whose orbital motion has a period of 1.1 day and a semimajor axis of 0.3 mas. Phase-referenced VLBI observations

of σ^2 CrB were conducted at 12 epochs between May 1987 and August 1992. These epochs are listed in Table 1.

At 5 GHz, our program used a VLBI array composed of the following antennas: the phased VLA (NRAO, N.M.), Bonn (MPI, Germany), Medicina (Bologna, Italy), Greenbank (NRAO, W. VA.), Haystack (MIT, MA.), OVRO (Caltech, CA.). At 8.4 GHz, the VLBI array initially included the 70-m DSN antenna at Goldstone (JPL, CA.), Hat Creek (Berkeley, CA.), OVRO (Caltech, CA.), Haystack (MIT, MA.), and the VLA (NRAO, N.M.). More recently, our experiments at 8.4 GHz have used the 70-m DSN antenna at Goldstone and several of the newly commissioned VLBA antennas (usually Brewster, Fort Davis, and North Liberty). The total data integration times were between 5 and 8 hours at each epoch. The Mark-III VLBI data acquisition system was used to record a bandwidth of 28 MHz (Rogers *et al.* 1983). The corresponding detection threshold is about 2 mJy (10 σ). All the cross-correlation of the recorded signals was carried out on the Mark-III VLBI processor at the Haystack Observatory. We use a non-standard fringe searching technique in which the residual geometric delay and fringe rate derived from strong reference source fringes are used to detect the much weaker fringes from the star.

TABLE 1 VLBI Observations of σ^2 CrB at 12 Epochs

Obser. Date	Orbital phase (cycle)	Frequency (GHz)	Flux density (mJy)
87/05/26	0.56	5.0	10
88/11/16	0.93	5.0	28
89/04/13	0.25	5.0	7
90/04/21"	0.53	8.4	6
90/11/16	0.37	5.0	3.8
91/10/12	0.86	8.4	19.5
91/09/14	0.53	5.0	4.3
92/01/15	0.88	8.4	4.6
92/04/05	0.96	8.4	18
92/04/22	0.76	8.4	6
92/06/08"	0.89	5.0	13
92/08/03	0.06	8.4	8.3

The 5 astrometric parameters of σ^2 CrB (2 coordinates, 2 proper motion components, and parallax) were estimated by a least squares fit with the 24 coordinates measured at the 12 epochs. Figure 1 shows the results of the fit. The uncertainties of the measured VLBI coordinates were set to 0.2 milli-arcsec to make the reduced- χ^2 close to unity for the number of degrees of freedom in the fit (19). The weighted rms of the post-fit coordinate residuals is 0.2 mas. With such an adjustment, the formal uncertainties for the 5 fitted parameters are 0.08 mas for the relative position 1) Ceti cell σ^2 CrB and the reference source 1611-1343, 0.04 mas/year for the proper motion and 0.08 mas for the trigonometric parallax. The correlation matrix indicates that the 5 parameters are well separated.

POST-FIT POSITION RESIDUALS FOR THE STAR σ^2 CrB

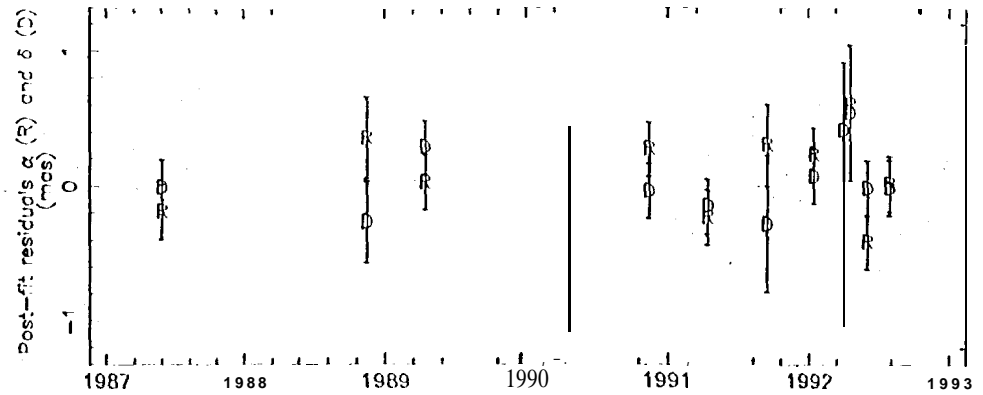


Fig. 1. Result of the fit of the 5 astrometric parameters of σ^2 CrB adjusted to the coordinates measured by VLBI at 12 epochs.

The number of degree of freedom (19) is high enough to make the statistical significance of the formal uncertainties reliable. Various tests have been made for the robustness of the solution. One test has been to make two separate astrometric solutions, one with the first 6 epochs and one with the last 6 epochs of Observations. Table 11 below indicates the parameter differences between the two solutions.

TABLE II Differences Between Two Astrometric Solutions

Parameter	Differences	$\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}$
$\Delta\alpha$	+ 0.18 mas	1.07
$\Delta\delta$	- 0.32 mas	1.57
$\Delta\mu_\alpha$	+ 0.02 mas/yr	0.2 σ
$\Delta\mu_\delta$	- 0.14 mas/yr	1.5 σ
An	-0.01 mas	0.10

Also, the 5 astrometric parameters of σ^2 CrB determined by VLBI match, within uncertainties, the best (but less precise) optical determinations.

IMPLICATIONS FOR THE PRESENCE OF PLANETS AROUND σ^2 CrB

The lack of a sinusoidal signature in the post-fit coordinates residuals of Figure 1 sets a limit on the presence of planets around σ^2 CrB. The rms of these

post-fit residuals (0.2 mas) is an upper limit on systematic departure from linear motion for the star. Eq. (1) can be used to exclude a range of planetary perturbations by taking $2\theta = 0.2$ mas, $M_* = 2.26 M_\odot$, and $d = 22.7$ pc for σ^2 CrB. The log-log representation of eq (1) with these parameters is shown in Figure 2. The diagonal line of constant astrometric signature follows eq. (1) and all points above this line represents larger planetary perturbations. We assume that a full orbital period of the planet must be sampled during the total span of observations to separate the sinusoidal planetary signature from the fitted linear proper motion. In these conditions, the maximum semimajor axis a of a planet corresponds to the total observation span through the third Kepler law. This upper limit on a is 3.8 AU for our 5 years of observations and is the vertical dashed line in Figure 2. The shaded area indicates the parameter space (a, m_p) that are excluded by our observation for a possible planet. Note that for $a = 3.8$ AU, the mass m_p is $0.0014 M_\odot$, i.e. 1.4 times the mass of Jupiter. Finally, on Figure 2, we have also shown where a Jupiter-like planet would fall. Interestingly, the present accuracy of our VLBI measurement corresponds exactly to the detection threshold for a J1113-like planet around σ^2 CrB when 12 years of data are collected.

RELATIONSHIP BETWEEN THE ASTROMETRIC MEASUREMENT UNCERTAINTY AND THE MINIMUM DETECTABLE PLANETARY PERTURBATION AROUND σ^2 CrB

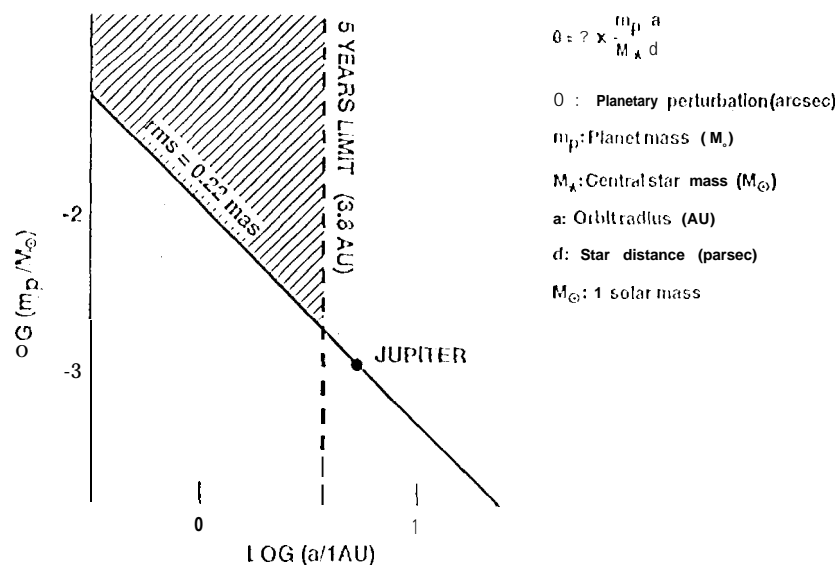


Fig. 2. Log-Log representation of eq (1) for the rms of the post-fit coordinate residuals of σ^2 CrB. The shaded area is the parameter space (semi-major axis a , mass m_p) that are excluded by our observations for a planet orbiting this star.

This interpretation is optimistic since Black and Scargle (1982) note that the fitted linear proper motion absorbs part of the planetary perturbation. These authors show that with observations sampling a single orbital period, the amplitude of the planetary perturbation is underestimated by as much as 47%. However, if the classical model (position, proper motion and trigonometric parallax) is complemented by a sinusoidal function and the *a priori* values for the amplitude, period and phase chosen to cover a large volume of the parameter space, no absorption of the planetary perturbation would occur and the 3 additional parameters can be fitted.

σ CrB is a triple system consisting of a visual pair with a G1V star (σ^1 CrB) separated by 140 AU ($P=1000$ years) from a spectroscopic binary (σ^2 CrB = F6V/F8V) whose separation is $6 R_{\odot}$ ($P=1.13$ day). The two orbital planes are coplanar (Barden 1985). The radio emission is identified with the spectroscopic binary classified as an RS CVn with two chromospherically active stars. The masses of these two stars, F6V and F8V, are 1.12 and 1.14 M_{\odot} (Barden 1985), respectively, and their sum, 2.26 M_{\odot} , has been used in the analysis above.

The location of the radio centroid within the spectroscopic binary is a crucial question. If the radio emission is associated with only one of the stars, then a peak-to-peak displacement of 0.6 mas correlated with the orbital phase of the system would be seen in our coordinates residuals since the observations were taken at various orbital phase of the spectroscopic system. A precise ephemeris of orbital phase has been established for σ^2 CrB by Bakos (1984). The post-fit residuals might be dominated by this orbital motion and we are investigating this possibility with additional observations to cover the whole orbit uniformly. The stability of this radio centroid over time is an important question for a planetary search. There is no detailed model of the radio emitting region that can be used to derive this stability. It must be determined observationally and the rms of our post-fit coordinate residuals (0.2 mas or $1 R_{\odot}$ at σ^2 CrB) can also be interpreted as a measure of this stability. If the radio emission is coincident with one of the stars as expected, then the astrometric error induced by its motion around the other star could be reduced dramatically by solving for the binary motion. We have confirmed that the radio emission is indeed associated with a single star in the Algol system (Lestrade *et al.* 1993).

FUTURE VLBI ASTROMETRIC OBSERVATIONS TO SEARCH FOR PLANETARY COMPANIONS

As a by-product of our Hipparcos program, we have demonstrated that phase-referenced VLBI observations of the radio star σ^2 CrB can achieve an astrometric precision of 0.2 mas (post-fit position residuals). Interestingly, this precision corresponds about to the level of perturbation around the linear proper motion of the star expected for a J101105-like planet over several years. Similar results have been obtained for the other stars of our Hipparcos program but with an astrometric precision 3 to 5 times larger. The best result is for σ^2 CrB because the angular separation between this star and the reference source used is the smallest (0.5°).

The theoretical astrometric precision (SNR-limited) for phase-referenced interferometry is

$$\sigma_{\alpha,\delta} = \frac{1}{2\pi} \frac{1}{\text{SNR}} \frac{\lambda}{B} \quad (1)$$

(Thompson, Moran, and Swenson 1986). For our observations, $\sigma_{\alpha,\delta}$ is 20 microarcseconds with $B = 3000$ km, $\lambda = 6$ or 3.6 cm and $\text{SNR} > 15$.

Table III summarises the relevant information for the 7 radio-emitting stars four proposed astrometric search program in order to compute the total sky displacement $2 \times \theta$ from eq. (1) expected for a Jupiter-like planet around these stars. The magnitude of $2 \times \theta$ in the last column of this Table compare favorably to the potential SNR-limited astrometric precision (eq. 2) of phase-referenced VLBI observations on US-continental baselines ($B = 4000$ km).

The last 2 stars in Table III (Hubble 4 and HD1283572 of the Taurus-Auriga dark clouds) are Pre-Main-Sequence stars that are not part of our current, Hipparcos program but have been detected on intercontinental VLBI baselines by Phillips, Lonsdale and Feigelson (1991). These **two** stars were also part of a survey at 1.3 millimeter and were not detected while others stars of the cloud were detected. The 1.3 millimeter detections were interpreted as evidence for a dust, disk around the stars, *i.e.* proto-planetary material (Beckwith *et al.* 1990). So one can speculate that Hubble 4 and HD1283572 are more evolved and, possibly, that their initial dust-disks have already collapsed into planets.

TABLE III The 7 Radio Stars of our VLBI Program

Star	Class	Distance (pc)	Masses (M_{\odot}) hot/cool	Spectral Type	$2 \times \theta_{\text{Jupiter}}$ (μas)
UX Ari	RS CVn	50	>0.63/>0.71	G5V/K0IV	<160
II R1099	RS CVn	36	1.1/1.4	G5IV/K1IV	100
HR5110	RS CVn	53	1.5/0.8	F2V/G0IV	80
σ^2 CrB	RS CVn	21	1.12/1.14	F6V G0V	210
AR Lac	RS CVn	47	>1.3/>1.3	G2IV/K0IV	<80
Hubble 4	PMS	160	0.5	2.0 K7.5	>30
HD1283572	PMS	160	0.5	2.0 G5.5	>30

The astrometric precision achieved for σ^2 CrB (0.2 milliarcsecond) is ten times the SNR-limited precision calculated above (20 microarcseconds). There are at least three systematic error sources that prevent current observations from reaching this ultimate precision: 1) the extrapolation of the reference source VLBI phase in beam-switched observations to the time of the star observation, "2) the differential contribution of the atmosphere and ionosphere along the two lines of sight to the reference source and target star, and 3) the radio morphology of the reference source and, possibly, of the star.

During the next 1-2 years, we intend to study the best approach to reduce these systematic errors:

- 1) by using faster switching time between observations of the star and reference source possible with the new VLBA antennas.
- 2) by using GPS data to calibrate the ionosphere. Dual-frequency GPS receivers should be installed at all VLBA antennas, shortly.
- 3) by breaking our VLBI observations into 3-hour segments to interleave 1-hour observations of standard astrometric calibrators to calibrate the troposphere.
- 4) by searching for closer reference sources than the ones we used for our Hipparcos program. Closer reference sources ($\leq 0.5^\circ$) should be found at least for some of the 7 proposed stars. Their radio flux density will likely be weaker but we shall determine their absolute position relative to our current reference sources by conducting phase-referenced VLBI observations. This "bootstrap" procedure will yield at least 1 milliarcsecond accuracy for the reference source and this will be entirely sufficient to measure the small differential position perturbation of the star caused by a planet.
- 5) by mapping the reference sources and accounting for the corresponding source structure in our differential measurement.
- 6) by upgrading the software SPRINT (Software for Phase-Referenced INterferometry) that we have developed for the Hipparcos-related VLBI program whose astrometric accuracy was less stringent than for the proposed program.
- 7) by incorporating orbital motion of the subgiant (in binary systems) into our astrometric fitting software.

Over the next three years, we plan to use one star, σ^2 CrB, as a test-bed to reduce the present systematic errors in our astrometric measurement and, possibly, reach the SNIL-limited precision of 20 microarcsecond on US-continental baselines. The sensitive Deep Space Network 70 meter antenna at Goldstone along with the US-continental VLBA antennas in Washington State, New Mexico, Arizona, Texas, Iowa, and New Hampshire will provide a relatively continuous range of baselines from 1000 km to 4000 km which correspond exactly to the angular resolution that is required for the RSCVn non-thermal radio stars we propose to observe. We shall also search for suitable new angularly closer reference sources to all the 7 stars in the Table above. Finally, we shall initiate a long-term program of VLBI observations to detect possible planetary perturbations around their linear proper motion. This obviously will involve observations at least as long as 10 years.

We have not included any nearby radio emitting red dwarf stars (dMe) in our current list of target stars because our strategy of observations requires that the stars be reliable at a flux density level of 2 mJy. The stars in the table above are highly variable but their flux density history shows that they are all reliable at the 2 mJy level. This minimum required flux density will decrease when the Green Bank Telescope and wider bandwidth VLBI recording systems (Mark-IV) become available. At that time it will be possible to significantly increase the list of nearby stars to which this planet search technique can be applied.

SUMMARY

The detection of other planetary systems is fundamental to increasing our understanding of the origin, evolution, and frequency of such systems. Many planet detection techniques are being developed, each with its own strengths and weaknesses. The major strength of high-precision VLBI astrometry is that it is already close to demonstrating an ability to detect or rule out the existence of gas giant planets orbiting nearby radio-emitting stars. In addition, its application to this field requires no new facilities or instrumentation. The major weakness of VLBI is that it allows us to study planetary systems around only relatively unusual stars. However, the recent discovery of planets orbiting a pulsar demonstrates rather spectacularly the fact that planetary systems need not be associated only with "normal" stars. Indeed, one of the basic questions about the origin of solar systems and extraterrestrial life is the range of conditions under which planets can form. Future VLBI searches for planets orbiting radio-emitting stars would provide valuable data to help answer this question.

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